Heraeus summer school 2019, Jena

Università degli studi di Padova, dipartimento di Fisica e Astronomia

Supernovae in the age of Gravitational Lensing

The multi-imaged SN Refsdal

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Introduction

Focus on the so called Refsdal Supernova (SN Refsdal):

- Brief history of Refsdal SN

The tools of gravitational lensing:

- How to model a lens
- Time delay
- A way to measure H_0

Statistical methods: how to find lensed SNs
Simulating a lensed SN event

Refsdal Supernova

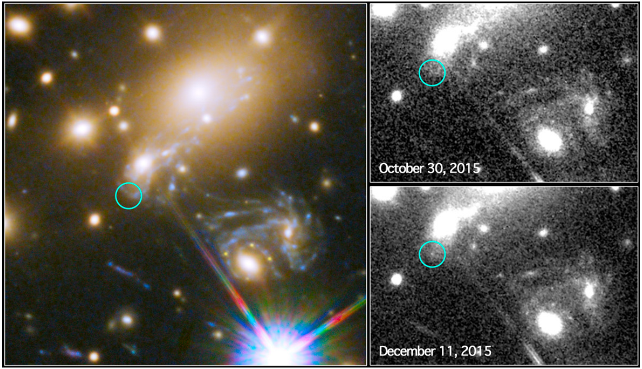
- First detected multiply-lensed supernova (11-th November 2014)
- The lens: an elliptical galaxy of the cluster MACSJ1149.6+2223.
- Reappered at the predicted position between mid of November 2015 and 11th December 2015

Figure: Sjur Refsdal, 1935-2009.

Example of Strong Lensing

- Observer: HST
- Lens: elliptical galaxy in the cluster MACS J1149.6+2223; $z = 0.54$
- Source: Refsdal Supernova inside a spiral galaxy; $z = 1.49$
- Advantages: short variability timescale absolute luminosity can be determined

Different appearances of the SN



From NASA, ESA and P. Kelly (University of California, Berkeley).

- Left: part of the deep field observation of the galaxy cluster MACS J1149.5+2223
- Top right: observations by Hubble from October 2015
- Low right: discovery of the Refsdal SN on the 11th of December 2015, as predicted by several different models

How to model a lens

- Example of density profile: Navarro-Frenk–White (NFW)

$$\rho(r) \propto r^{-1}(r+r_s)^{-2} \quad \begin{cases} r^{-3} \text{ for large } r \\ \infty \text{ for small } r \implies \text{ simple model!} \end{cases}$$

- Connection with deflection angle:

Deflection angle-potential

$$\alpha = \frac{2}{c^2}\int \boldsymbol{\nabla}_\perp \phi \, \mathrm{d}\lambda$$

Potential-density (Poisson)

$$\nabla^2 \phi = 4\pi G \rho$$

- Find parameters of interest (convergence κ, Einstein radius θ_{E}, shear etc.)

Time delay

- For multiple images, different paths for the light rays $\rightarrow$ different arrival times
- The time delay can be measured using transient objects, like supernovae

$$\Delta t_{ij} = \Delta t_{fid}\,\Phi(\theta_i \theta_j)$$

- $\Phi(\theta_i \theta_j)$ depends on the image configuration $\rightarrow$ estimated by lens model
- $\Delta t_{fid} = \frac{1+z}{c}\frac{D_{ol}D_{os}}{D_{ls}}\theta_E^2 \quad \rightarrow \quad$ the ratio $\frac{D_{ol}D_{os}}{D_{ls}}$ gives H_0
- The standardizable candle nature of Type Ia supernovae allows us to directly measure the magnification factors $\implies$ break degeneracies found in other variable sources

Measurements of H_0

- We can use the time delay to constrain H_0: this parameter sets the absolute length scale of the Universe $\rightarrow$ determines the difference of the light rays paths $\rightarrow$ time delay
- The time delay distance depends not only on H_0, but also on Ω_m, w_{de} $\rightarrow$ time delays provide information complementary to other cosmological probes
- Independent H_0 measurements are needed, because of the tension

CMB		distance ladder
$H_0 = 67.4 \pm 0.5$ km/s/Mpc	$\longleftrightarrow$	$H_0 = 74.03 \pm 1.42$ km/s/Mpc

How to find other lensed supernovae

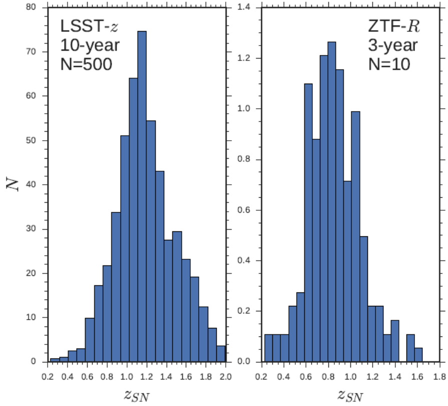
Monte Carlo simulations:

- model for the lenses: mass, velocity and redshift distribution functions
- model for the SN: two different models for SN Ia or core-collapse
- see number of detections possible with different surveys

Dependence on the cosmological model.

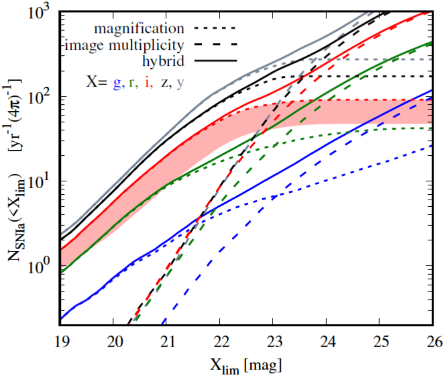
Contamination by abnormally luminous non-lensed SN or AGNs.

How to find other lensed supernovae



Redshift distribution of the 500 multiply imaged SN Ia detectable by this method in a 10-year LSST z-band search (left) and the 10 detectable a 3-year ZTF R-band search (right) by the calculations of Goldstein and Nugent (2016).

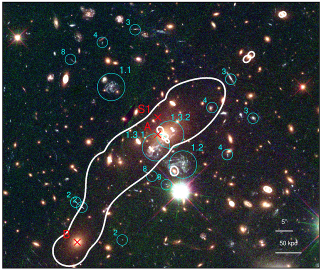
How to find other lensed supernovae



Detection rates of strongly lensed type Ia supernovae as a function of survey depth in different bands, in an all-sky search. The long dashed curves represent the multiply imaged SN and the short dashed ones the magnificated images, while the solid curves represent an hybrid method combining the two. (Wojtak et al. 2019)

Understanding the system

- We started from HST observations: many background sources
- We used the mass profile described by a paper by Rau et al.
- We can recreate Lens by Lens the cluster in Python



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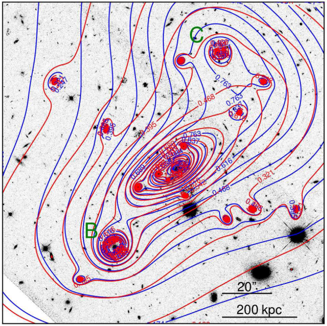

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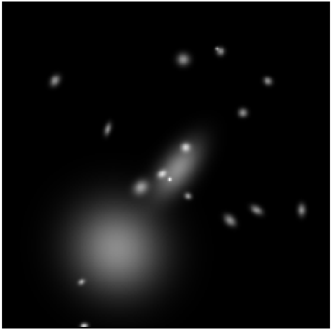
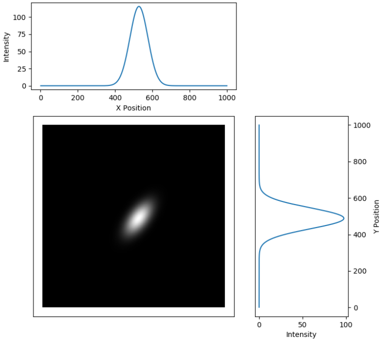


Understanding the system

- Lenses are described by Gaussian blobs



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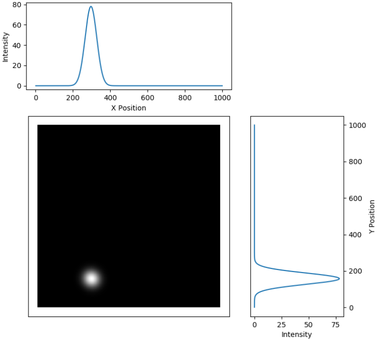

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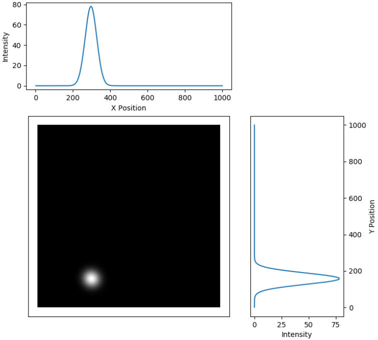

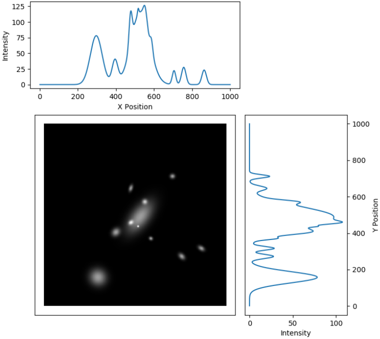

Simulating the Cluster

- Simplified model: no mass sources like DM
- Outcome is imprecise but can showcase the effects of a more complex lens

Simulating the SN event

- We took a SN Ia, as their light curves are standard
- Simulation takes place in the 50 days after the explosion
- Lens is the elliptical galaxy lensing SN Refsdal
  Source is a gaussian blob where the SN event takes place

Conclusions

- SN Refsdal and its importance
  - unique properties of the SN
  - models of strong lensing and mass distribution of the lens
  - constraint on H_0
- Statistical methods to find other multiply-imaged SN
- Simulation to better understand the phenomenon